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Description of an Oscillating Flow Pressure Drop Test Rig

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ABSTRACT

This paper describes a test rig designed to generate heat exchanger pressure drop information under oscillating flow conditions. This oscillating flow rig is based on a variable-stroke and variable-frequency linear drive motor. A frequency capability of 120 hertz and a mean test pressure up to 15 mPA (2200 psi) allows for testing at flow conditions found in modern high specific-power Stirling engines.

An important design feature of this rig is that it utilizes a single close-coupled dynamic pressure transducer to measure the pressure drop across the test sample. This eliminates instrumentation difficulties associated with the pressure sensing lines common to differential pressure transducers. Another feature of the rig is that it utilizes a single displacement piston. This allows for testing of different sample lengths and configurations without hardware modifications. All data acquisition and reduction for the rig is performed with a dedicated personal computer. Thus the overall system design efficiently integrates the testing and data reduction procedures.

This paper describes the design methodology and details of the test rig. A description of the data reduction and analysis routines is also given.

BACKGROUND

Very little information is available concerning flows under oscillating conditions such as those which exist in the heat exchangers of Stirling engines. A thorough review of the available information has been performed by Seume and Simon (1) at the University of Minnesota.

Analytical solutions for oscillating flow pressure drops exist only for laminar oscillating flow, and these solutions neglect entrance and exit effects. The flow in the heat exchangers of Stirling engines however is most often turbulent oscillating flow, and is of course subject to entrance and exit effects. Therefore, experimental information is needed which could be applied to the design and optimization of Stirling engines. At present this experimental information is largely non-existent.

These pressure drop measurements are rather difficult to perform in running engines. This is due in part to the high temperatures that exist in some of the spaces where measurements need to be made. Most of the difficulty however arises from the use of differential pressure transducers which rely on connecting tubes to sense the pressure differentials. These connecting tubes, and the associated volumes at the connections to the transducer, are subject to resonance effects and must be carefully designed to avoid erroneous measurements.

Even if this measurement is done correctly in a running engine, the results obtained are only applicable to the heat exchanger types and configurations which exist in the engine. The flow regimes over which the given piece of hardware can be operated are also usually quite restricted. For these reasons, the information which can be obtained from running engines is limited.

The lack of knowledge concerning oscillating flow pressure drops is more important to the design and operation of FPSEs (free-piston Stirling engines) than for kinematic (mechanically constrained motion) engines. In kinematic engines pressure drops generally influence only power output. In FPSEs however these effects also influence the motions of the moving components, since these parts are not connected to a mechanical linkage. The result being that in FPSEs these pressure drop effects can have a magnified impact on engine performance.

A better understanding of oscillating flow pressure drops is needed in order to design more efficient and higher specific power engines. A review of the need for this information, as well as for information on the other losses in Stirling engines, is presented by Tew (2). This need was the impetus for designing the test rig described in the following text. This rig was designed at Sunpower Inc. under a NASA SBIR contract; it is presently being used to generate test information.

CONCEPTUAL DESIGN

The approach taken in the design presented here is different from that being pursued in a rig designed by Seume (3). The approach of the Seume rig is to scale the test sample size up several times and reduce frequency and pressure so that measurements can be made within the sample.

The approach taken in the Sunpower design is to test true-size samples as near as possible to actual operating conditions. Two exceptions to this are made. First, all test samples are run near room temperature; and secondly, mean cyclic pressure variations such as occur in Stirling engines are not included (at least not in early testing).

Since the heat exchangers tested with the Sunpower rig usually have small passages, it would be essentially impossible to make measurements within the test sample. Rather than attempt this, the rig is used to measure the total pressure drop across the sample. The intended purpose of this rig is to generate a data base of pressure drop information for a large group of different sample types and configurations and to do this over a wide range of flow parameters.

The different approaches taken in the Sunpower and Seume rigs are intended to produce results which cross-check and complement each other. A third rig under test at Argonne Labs and described by Roach (4) will also help toward the better understanding of oscillating flow effects.

In order to achieve a wide range of frequencies and piston displacements, the Sunpower rig is based on a linear drive motor. The piston which produces the oscillating flow through the test sample is directly attached to this drive motor. A cross-sectional drawing of the rig is shown in Figure 1. The individual components of the rig are labeled in the schematic drawing of Figure 2. This rig is approximately 0.3 meter in diameter and 1.0 meter in length.

The use of this linear drive motor has several advantages. The stroke of the motor is simply varied by adjusting the driving voltage. Thus no hardware modifications are required to run tests over the range from zero to the full stroke capability (3 cm.) of the rig. The frequency of the linear drive motor is also easily adjusted (within a given range described below) simply by adjusting the frequency of the drive voltage applied to the motor.

Although in theory it would be possible to design a drive motor capable of supplying all the required driving force, this is not practical. A more feasible approach, used in the Sunpower rig, is to use springs to balance the inertia forces of the reciprocating parts of the rig. The spring-mass combination of the rig is tuned to mechanical resonance near the desired range of testing. How far removed from this frequency that the rig can be operated is determined by the electrical current capability, and thus peak driving force available from the motor.

Mechanical rather than gas springs were chosen for the design. The rig is set up before a run for operation near the desired frequency by installing springs to tune the moving mass of the rig to that frequency. With a given set of springs installed, the frequency of the rig can still be varied over a range of approximately 10 to 20 hertz.

From the onset of the project it was realized that the rig's wide range of operating frequencies would complicate the problems described earlier of using differential transducers with sensing lines. Also recognized was that the intended testing of numerous sample lengths and configurations would require many changes to the length of these sensing lines.

In order to address this instrumentation problem, and thus reduce the chance of introducing errors, the rig layout shown in Figures 1 and 2 was selected. This arrangement surrounds the drive motor, displacement section, and test sample by a pressure enclosure. The volume of this enclosure is much larger than the volume displaced by the piston of the rig, so the pressure in this space is essentially constant during rig operation. Because of this constant pressure, the pressure drop across the test sample can be measured by a single close-coupled pressure transducer in the displacement section.

The pressure transducer used for measuring the dynamic pressure in the displacement section is a silicon diaphragm type which has the back side of the diaphragm ported to the large interior volume of the pressure enclosure. This method allows the use of a sensitive pressure transducer even though the mean test pressure is quite high.

Besides simplifying instrumentation requirements this arrangement also simplifies the testing of samples. The arrangement requires no hardware modifications to test different sample types and lengths. To change samples, it is only necessary to open the pressure enclosure for access to the sample mounting area.

The rig design requires only two dynamic measurements to be made, these being the pressure in the displacement section and the position of the piston. Static measurements recorded include the mean pressure and temperature within the pressure enclosure as well as gas and metal temperatures at the displacement section. The wall temperature of the test sample is also measured.

Currently the test rig does not perform tests with the significant cycle pressure variations such as exist in Stirling engines. This could be performed in the future by installing a second motor and displacement section at what is now the open end of the tube. Considerations are also being given to modifying the existing rig so that heat transfer testing could be performed.

STEADY UNIDIRECTIONAL FLOW TEST RIG

A steady unidirectional flow test rig was also designed under this program. The purpose of this rig for tube-type heat exchangers is to verify the unidirectional pressure drop of samples against accepted correlations. This rig will also be useful for generating unidirectional flow information for samples for which no reliable information exists; such as is the case for certain types of regenerator samples.

A schematic drawing of this rig is presented in Figure 3. Physical dimensions of this rig are approximately 1.0 meter diameter for the main pressure vessel and an overall length of 2.0 meters. Flow through the loop is provided by means of a piston-type compressor which is driven by a variable speed DC motor. Gas from the compressor flows into an accumulator tank which is provided to suppress pressure pulsations caused by the compressor.

After leaving the accumulator, gas flows first through the element labeled 'filter' in Figure 3. This element is a dense porous metal plug, and is included more as a flow restriction to help eliminate pressure pulsations than for filtering.

After leaving the filter, gas flows through a mass flow sensor and then into the small pressure vessel shown in Figure 3. Gas then flows through the test sample and into the large pressure reservoir of the main pressure vessel.

Pressure drop across the test sample is measured by a differential pressure transducer with sensing lines. Since the flow in this rig is steady, the response problems mentioned earlier for this type of transducer arrangement do not occur.

The cooling coils and fan shown in the figure are not normally necessary. These were provided only for use in the event that testing of high pumping power samples would result in significant temperature rises of the system.

RANGE OF POSSIBLE OPERATING PARAMETERS

The design philosophy of the oscillating flow rig allows for a wide operating range. This operating range is summarized in Table 1.

TABLE 1.

Oscillating Flow Rig:

Maximum Mean Pressure	15.0	mPa	(2200 psi)
Maximum Frequency	120.0	Hz	
Maximum Stroke *	3.0	cm	(1.18 in)
Maximum Sample Length	36.0	cm	(14.2 in)

* See Text

The maximum physical stroke of the piston is 3 cm, as indicated in the table. However, the rig relies on dry-running teflon-based bearings for alignment. These bearings inherently have a limiting peak velocity at which they can be run without experiencing excessive wear. This velocity is approximately 5.7 m/sec. Therefore at frequencies above 60 hertz the rig is normally run at a reduced stroke. At 120 hertz for instance the velocity limit of the bearings requires that the stroke be limited to 1.5 cm. The rig has been sized to account for this; desired flow rates are still obtained at this reduced stroke.

For the steady flow test rig the maximum pressure is 5 mPa (725 PSI).

OPERATING PARAMETER CONTROL

The charge pressure for both rigs is controlled by manual charge and discharge valves. The other operating parameters for both test rigs are controlled from the instrument rack. For the oscillating flow rig these parameters are piston stroke and frequency, while for the steady flow rig, the single controlled parameter is mass flow rate.

The frequency of the oscillating flow rig is adjusted by means of a potentiometer which controls the switching frequency of a specially developed motor driver. Electrical input to this motor driver is rectified 3-phase power. Piston amplitude is controlled by adjusting the voltage of this 3-phase power using a variac.

Mass flow rate for the steady flow rig is also set using the variac. In this case the rectified 3-phase power bypasses the switching electronics and is directly applied to the DC motor.

DATA ACQUISITION SYSTEM

The same data acquisition system handles data monitoring and storage for both test rigs. This system is based on a dedicated personal computer.

For the oscillating flow rig, this system monitors the two dynamic signals (pressure drop and piston stroke) along with six steady signals (mean pressure and five temperatures within the rig). During rig operation the data system continually updates the status of all signals on the computer monitor. The steady signals and amplitudes of the dynamic signals are presented numerically in engineering units. The dynamic signals are also displayed graphically, either as waveforms or in terms of Fourier spectra. Examples of these two types of dynamic signal display are shown in Figure 4.

For the unidirectional flow test rig no dynamic signals occur and all test information is displayed in engineering units. Here the display includes calculated values of Reynold's number and the ratio of measured pressure drop to that predicted by accepted equations.

When desired, a single keyboard operation instructs the computer to record a data point. During this process the steady signals are averaged, while dynamic signals are Fast-Fourier transformed into nine harmonics plus a zeroth-order term. The averaged steady signals and the Fourier coefficients are printed as well as recorded on the hard disk of the computer.

DATA REDUCTION

For the oscillating flow rig the instantaneous mass flow rate through the sample is not measured directly but must be determined from the known position and pressure signals. The mass flowing past the interface of the cylinder and the test sample is determined by analyzing the cylinder volume as an initial value problem. This requires some values that are not known precisely, such as the heat transfer coefficient between the gas and the wall of the cylinder, and the temperature of the gas when it flows from the sample into the cylinder.

Uncertainties of these unknown values are handled by an error analysis which is part of the data reduction process. Other errors, such as the variation in mass flow along the length of the sample as well as the instrumentation inaccuracies, are also included in this analysis.

RESULTS OF EARLY TESTING

During early testing with this rig an unexpected phenomenon occurred. At small strokes and at certain piston frequencies, higher frequency oscillations in the pressure wave were experienced. These were determined to be Helmholtz-type oscillations of the gas in the tube resonating on the effective gas spring of the displacement cylinder. These oscillations could be excited whenever the Helmholtz frequency was an odd multiple of the driving frequency.

These resonant oscillations are strongly frequency dependent, and for most samples they can be tuned-out by slightly adjusting the frequency of the piston motion. The effects of these oscillations also diminish as piston stroke is increased so that the first harmonic pressure oscillation caused by piston motion overwhelms the Helmholtz oscillations.

Testing of various tube-type samples with this rig is now being performed and a data base of test information is being generated. This testing has included circular tubes of various length to diameter ratios in an attempt to determine an effective entrance/exit loss coefficient for oscillating flow. Similar testing has been performed on rectangular flow passages with various aspect ratios. Testing on regenerator matrices is planned in the near future.

SUMMARY

This paper presents a description of a test rig which is being used to generate heat exchanger pressure drop information for oscillating flow conditions. This information will provide a better understanding of oscillating flow; an understanding that will lead toward the design of more efficient and higher specific power Stirling engines.

The unique layout of the rig simplifies the testing of samples and largely reduces the possibility of instrumentation errors. A computer based data system is included to further provide for the efficient testing of samples. The intent of this rig is to produce a large data base on oscillating flow pressure drop information on many different types and configurations of heat exchangers.

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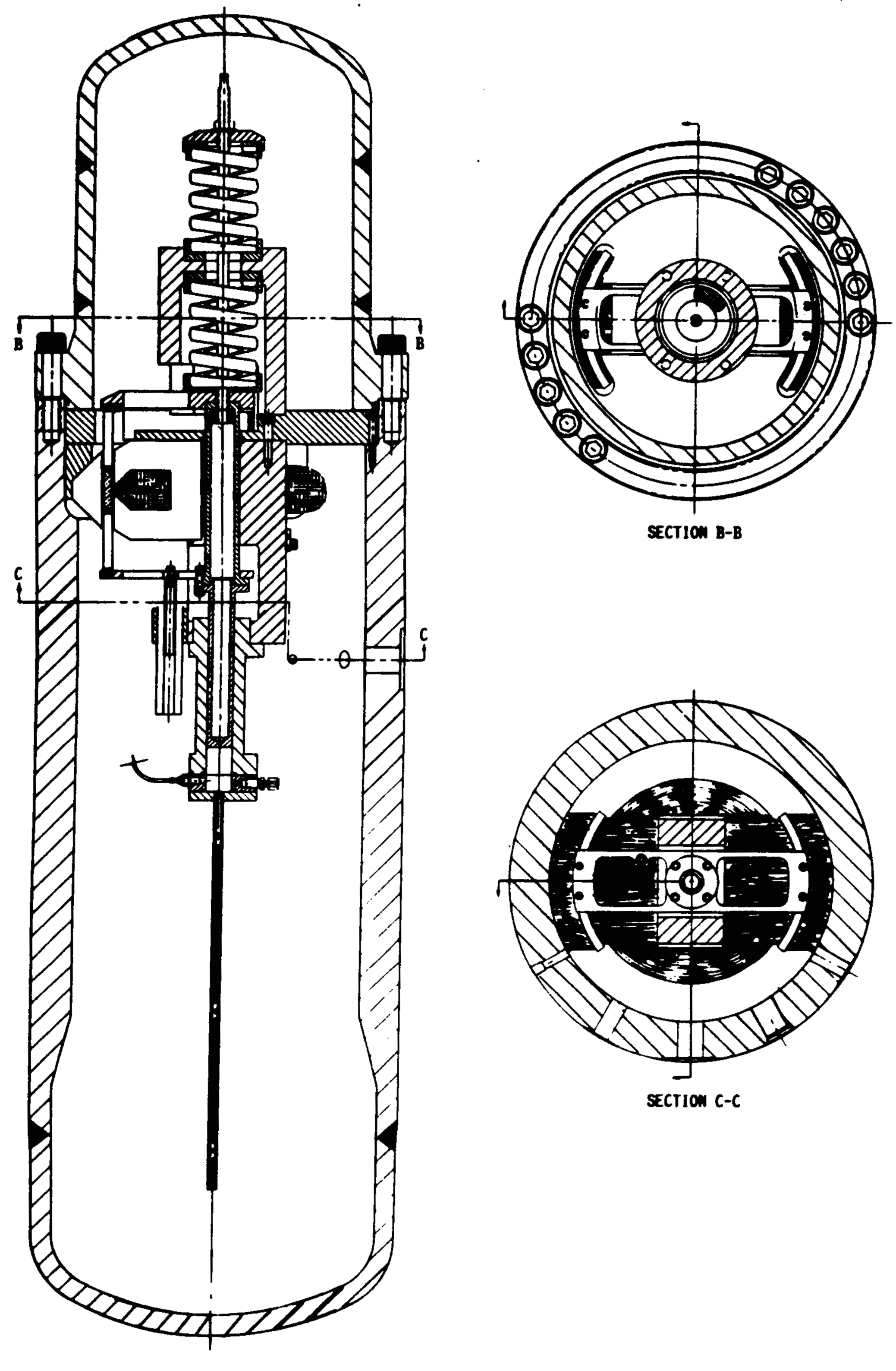

FIGURE 1. - OSCILLATING FLOW TEST RIG.

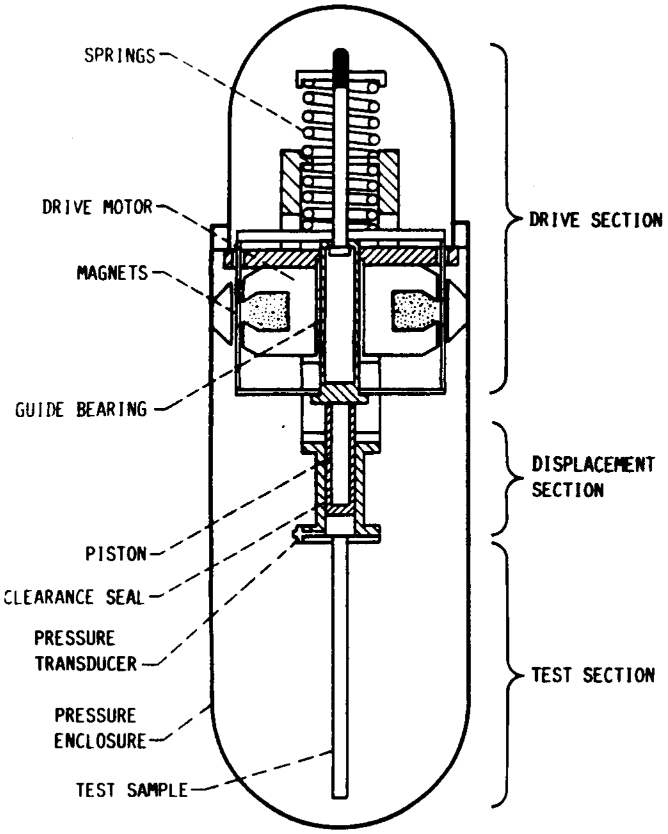

FIGURE 2. - OSCILLATING FLOW TEST RIG SCHEMATIC.

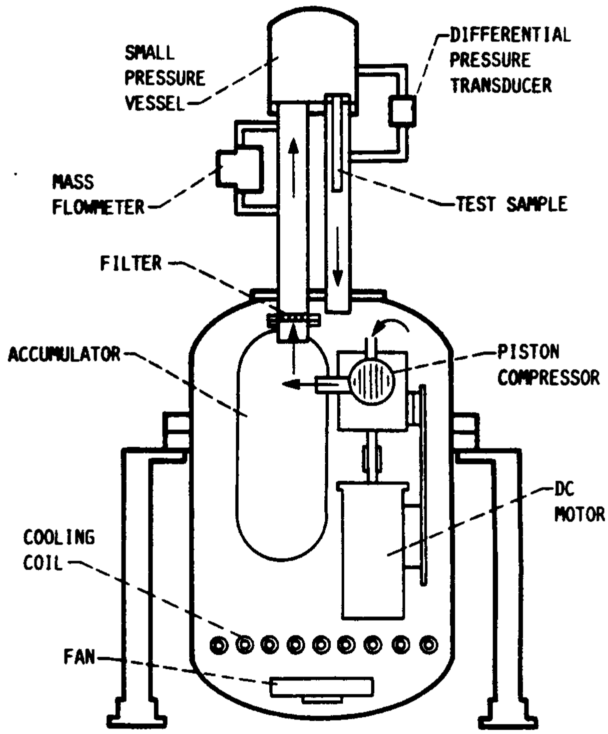

FIGURE 3. - STEADY FLOW TEST RIG.

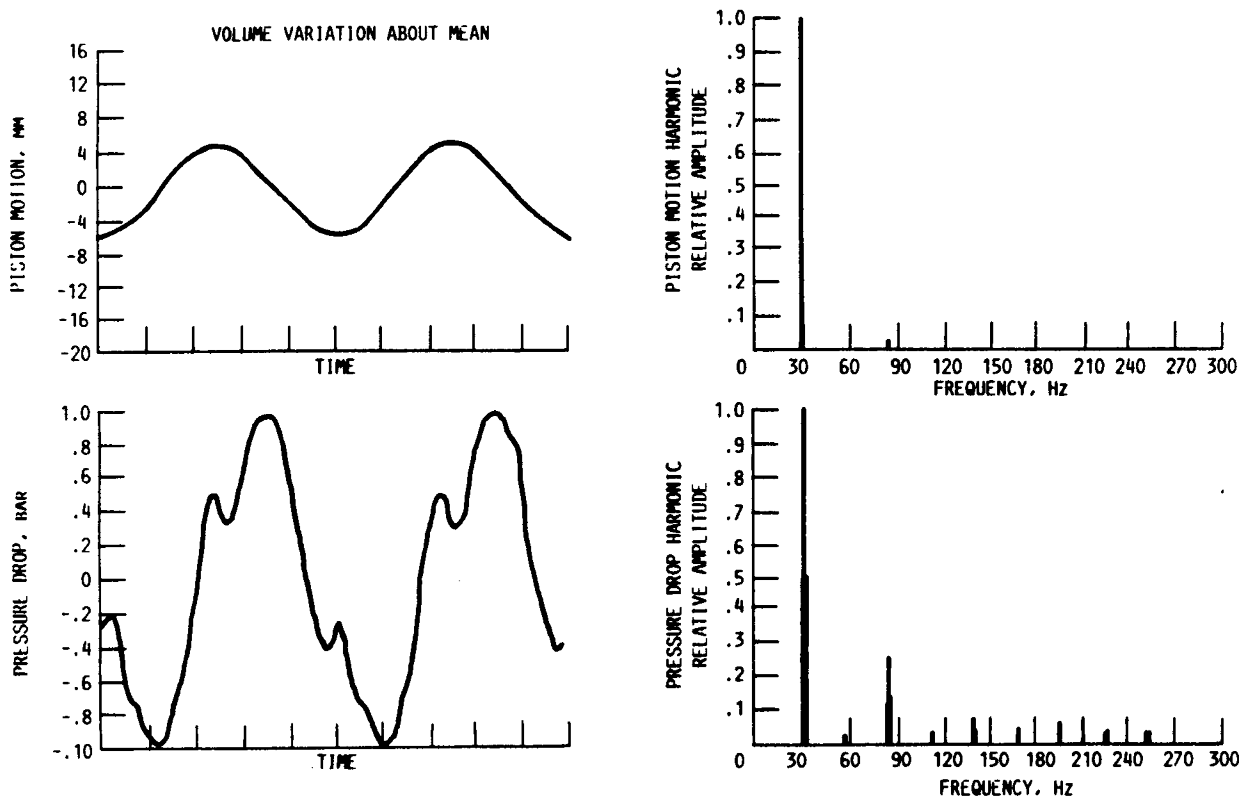

FIGURE 4. - OSCILLATING FLOW RIG DATA.

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16. Abstract

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